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Phys. Rev. C **86**, 044623 — Published 31 October 2012

DOI: [10.1103/PhysRevC.86.044623](https://doi.org/10.1103/PhysRevC.86.044623)

Disentangling effects of collision geometry and symmetry energy in U+U collisions

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Effects of the collision geometry on experimental observables that are known to be sensitive to the high-density behavior of nuclear symmetry energy are examined in U+U collisions at 0.52 GeV/nucleon using an isospin- and momentum-dependent interaction within the framework of IBUU transport model. It is found that the neutron-proton differential flow in tip-tip collisions and the difference of neutron and proton elliptic flow in body-body collisions are more sensitive to the symmetry energy at supra-saturation densities compared with collisions of spherical nuclei of the same masses. In addition, the n/p ratio of pre-equilibrium nucleons is found to be slightly more sensitive to the symmetry energy in tip-tip collisions, and the collision geometry affects the π^-/π^+ ratio significantly.

PACS numbers: 25.70.-z, 24.10.Lx, 21.65.-f

I. INTRODUCTION

Energetic heavy-ion collisions are the only way of producing high-density nuclear matter in terrestrial laboratories. All heavy nuclei are neutron-rich and many of them have a prolate or oblate shape in their ground states. While the role of deformation/orientation of nuclei in nuclear fusion/fission at low energies has been studied extensively for a long time, it is only during the past decade that we witnessed a surge of investigations making good use of the deformation/orientation of heavy nuclei in energetic nuclear reactions to probe interesting physics issues, such as properties of the Quark-Gluon Plasma (QGP) [1–8] and chiral magnetic effect [9] in relativistic heavy-ion collisions. It is exciting to note that U+U experiments at 193 GeV/nucleon have been done very recently by the STAR Collaboration at RHIC [10]. While waiting for the experimental results, it is worth mentioning that a very rich array of phenomena were predicted to occur in U+U collisions due to different relative orientations of the football-shaped uranium nuclei. Among all possible orientations, the tip-tip (with long axes head-on) and body-body (with short axes head-on and long axes parallel) collisions are the most interesting ones. In relativistic heavy-ion collisions, the central body-body U+U collisions provides a better system to study the properties of formed QGP compared with Pb+Pb or Au+Au collisions of similar eccentricity [3, 4]. Furthermore, the particle multiplicity, initial eccentricity, and final collective flow will be affected by the collision geometry [5–8]. At beam energies of a few hundred MeV/nucleon, tip-tip collisions normally have a larger stopping power and a longer high-density phase compared to body-body collisions [11, 12]. It has also

been found that the multiplicities of pions and free nucleons are different in tip-tip collisions and body-body collisions [11–13]. In addition, the transverse flow, which is an observable sensitive to the nuclear matter equation of state (EOS), is much larger in non-central tip-tip collisions than in non-central body-body collisions [11]. Moreover, the elliptic flow (v_2), which is another messenger about nucleon-nucleon interactions in dense matter, is different in tip-tip and body-body collisions as well [11–13]. While it is very challenging to select events of special orientations, such as tip-tip and body-body in U+U collisions, several promising triggers have been proposed in the literature [5, 14] and tested positively in model simulations.

Generally speaking, heavy nuclei are all neutron-rich especially in their surface areas. Moreover, protons and neutrons may have different deformations. There are considerable interests in the heavy-ion reaction community to carry out U+U collisions at intermediate energies to probe the density dependence of nuclear symmetry energy $E_{sym}(\rho)$ at 1-3 times normal nuclear matter density. For instance, U+U experiments at 0.52 GeV/nucleon have already been planned at the external target facility of the cooling storage ring at Lanzhou/China [15, 16]. The $E_{sym}(\rho)$ at supra-saturation density is among the most uncertain properties of dense neutron-rich matter and has many important ramifications in astrophysics [17–19]. Especially, the $E_{sym}(\rho)$ at 1-3 times normal nuclear matter density plays the most important role in determining the radii of neutron stars [20]. Does the U+U collisions really provide a better opportunity to probe the EOS of dense neutron-rich matter than reactions with spherical nuclei of similar masses? Suppose one can indeed trigger on collisions with specific orientations in U+U collisions, which orientation, tip-tip or body-body, may be a better choice to investigate the $E_{sym}(\rho)$ at supra-saturation densities? For a given orientation, what are the sensitive probes of the $E_{sym}(\rho)$? On the other hand, suppose one can not distinguish different orientations in U+U collisions in an unfortunate situa-

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tion, how big are the relative effects of nuclear symmetry energy and nuclear deformation/orientation on isospin-sensitive observables (isospin tracers) in inclusive reaction events? To help answer these questions, we examine relative effects of the collision geometry and nuclear symmetry energy in U+U collisions at 0.52 GeV/nucleon. Several $E_{\text{sym}}(\rho)$ -sensitive experimental observables in either tip-tip or body-body U+U collisions are identified. The results are expected to be useful for planning the U+U experiments at intermediate energies.

II. BRIEF MODEL DESCRIPTION

Our study is carried out within the isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [21]. To facilitate discussions of the IBUU results, we shall firstly describe briefly the effective nuclear interaction used in this study. The neutron and proton distributions in uranium nuclei are then outlined.

A. The isospin- and momentum-dependent interaction

The momentum dependence of the nuclear interaction is important in understanding not only dynamics in intermediate-energy heavy-ion collisions [22–24] but also thermodynamical properties of nuclear matter [25–27]. In the present study we use an isospin- and momentum-dependent interaction [28]. In this model, the mean-field potential of a nucleon with momentum \vec{p} and isospin τ is written as

$$\begin{aligned}
 U(\rho, \delta, \vec{p}, \tau) = & A_u(x) \frac{\rho_{-\tau}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} \\
 & + B \left(\frac{\rho}{\rho_0} \right)^{\sigma} (1 - x \delta^2) - 8\tau x \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \delta \rho_{-\tau} \\
 & + \frac{2C_{\tau, \tau}}{\rho_0} \int d^3 p' \frac{f_{\tau}(\vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2} \\
 & + \frac{2C_{\tau, -\tau}}{\rho_0} \int d^3 p' \frac{f_{-\tau}(\vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2}. \quad (1)
 \end{aligned}$$

In the above, $\rho = \rho_n + \rho_p$ is the nucleon number density and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry of the nuclear medium, with $\rho_{n(p)}$ the neutron (proton) density, $\tau = 1/2$ ($-1/2$) for neutrons (protons), and $f(\vec{p})$ is the local phase-space distribution function. The values of the parameters $A_u(x)$, $A_l(x)$, σ , B , $C_{\tau, \tau}$, $C_{\tau, -\tau}$ and Λ can be found in Refs. [28, 29], and they lead to the binding energy -16 MeV and incompressibility 212 MeV for symmetric nuclear matter and symmetry energy 30.5 MeV at saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$.

The above mean-field potential comes from a modified Gogny force including a zero-range effective three-body interaction and a finite-range Yukawa-type two-body interaction [28, 30], where the parameter x controls the

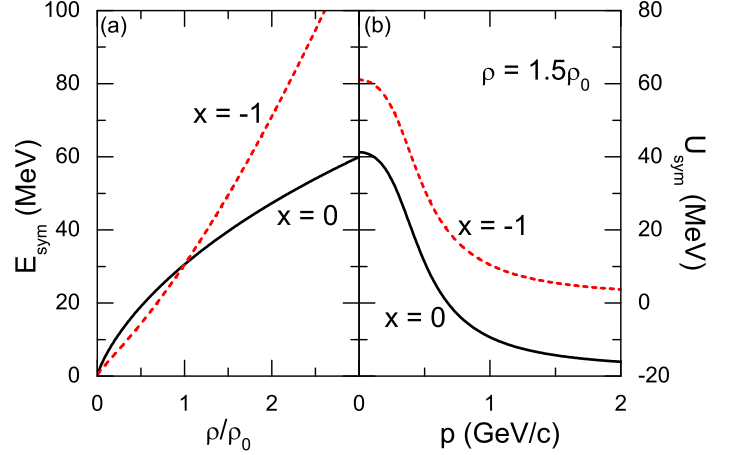


FIG. 1: (Color online) The density dependence of the symmetry energy (a) and the momentum dependence of the symmetry potential (b) at $\rho = 1.5\rho_0$.

relative contributions of the isosinglet and isotriplet interaction channels. By adjusting the value of x , the density dependence of the symmetry energy is modified while the value of the symmetry energy at saturation density and all the properties for symmetric nuclear matter remain unchanged. The analytical formula of the symmetry energy in this model can be found in Ref. [31]. From comparing the IBUU calculations with the isospin diffusion data, the value of x is constrained between 0 and -1 at densities around and below the saturation density of nuclear matter [29, 32]. The corresponding slope parameter $L = 3\rho_0(dE_{\text{sym}}/d\rho)_{\rho_0}$ is between $L = 60$ and 106 MeV overlapping with constraints extracted from studying several other observables using various approaches (see [33] and references therein). At supra-saturation densities, while the FOPI π^-/π^+ ratio data favors IBUU calculations using a super soft symmetry energy with $x = 1$ [34], the symmetry energy remains rather uncertain and much more studies of additional observables are very much needed. To evaluate the relative effects due to the collision geometry and the symmetry energy on isospin tracers, we use $x = 0$ and -1 in the whole density range in the present work. We emphasize that the current uncertainty range of the symmetry energy at supra-saturation densities is much larger than the one considered here [19]. Thus, the symmetry energy effects with respect to those due to geometry in U+U collisions studied here should be considered as being rather conservative. As shown in the panel (a) of Fig. 1, $x = -1$ leads to a stiffer symmetry energy which is smaller at subsaturation densities and larger at supra-saturation densities compared with $x = 0$. A stiffer symmetry energy generally leads to a larger isospin fractionation effect, i.e., a less neutron-rich high-density regime and a more neutron-rich low-density regime, to lower the energy of the whole system compared with a softer symmetry energy.

The mean-field potential from Eq. (1) can be approximately expressed as

$$U_{n/p}(\rho, \delta, \vec{p}) \approx U_0(\rho, \vec{p}) \pm U_{sym}(\rho, \vec{p})\delta, \quad (2)$$

where U_0 is the isoscalar mean-field potential, U_{sym} is the symmetry potential, and the \pm sign is for neutrons (protons). The momentum dependence of the symmetry potential at $\rho = 1.5\rho_0$ are plotted in the panel (b) of Fig. 1. It is seen that the symmetry potential is mostly positive, which means that generally neutrons feel a more repulsive potential than protons. In addition, the symmetry potential is larger for $x = -1$ at supra-saturation densities, thus neutrons are more likely to be emitted from while protons are more likely to be trapped in the high-density regime, resulting in a less neutron-rich high-density regime and a more neutron-rich low-density regime, consistent with the above discussion of the isospin fractionation effect. The decreasing trend of the symmetry potential with increasing momentum is consistent with the energy dependence of the Lane potential and leads to larger effective masses of neutrons than protons [35]. The in-medium nucleon-nucleon elastic cross sections are consistently modified from their free-space values according to the in-medium nucleon effective masses [32].

B. Initial density distributions

Compared to the uniform ellipsoid distribution as used in Refs. [11–13], a deformed Woods-Saxon distribution is more realistic for uranium nuclei [36]. In addition, various studies [37–42] have shown that neutron skin exists in deformed nuclei as well, and the deformations of neutron and proton distributions are different. For ^{238}U , we use Woods-Saxon distributions for neutrons and protons with different radii and deformations

$$\rho_{n/p}(r, \theta) = \frac{\rho_{n/p}^0}{1 + \exp[(r - R'_{n/p}(\theta))/a]}, \quad (3)$$

where

$$R'_n(\theta) = R_n[1 + \delta_n Y_2^0(\theta)], \quad (4)$$

$$R'_p(\theta) = R_p[1 + \delta_p Y_2^0(\theta)]. \quad (5)$$

In the above, $\rho_{n/p}^0$ is the normalization constant, $Y_2^0(\theta)$ is the spherical harmonics, and $a = 0.55$ fm is the surface diffuseness parameter. In the present work we use $R_n = 6.91$ fm for neutrons and $R_p = 6.71$ fm for protons, respectively. The deformation parameters are $\delta_n = 0.275$ for neutrons and $\delta_p = 0.285$ for protons, and $R_n\delta_n \approx R_p\delta_p$ is approximately satisfied.

III. RESULTS AND DISCUSSIONS

Let's first have a global picture of the body-body and tip-tip U+U collisions in IBUU transport model, as

shown in Fig. 2. Initially two uranium nuclei are placed at a distance along the z-axis with different orientations. As time goes on, collision happens and the central density can reach $2\rho_0$ or higher. The system is most compressed around 20 fm/c, when the interaction is the strongest and Δ resonances are abundantly produced. After 20 fm/c the system begins to expand and the density drops. One can expect the different dynamic processes in body-body and tip-tip U+U collisions from their different density evolutions, especially the longer duration time of the high-density regime in tip-tip collisions.

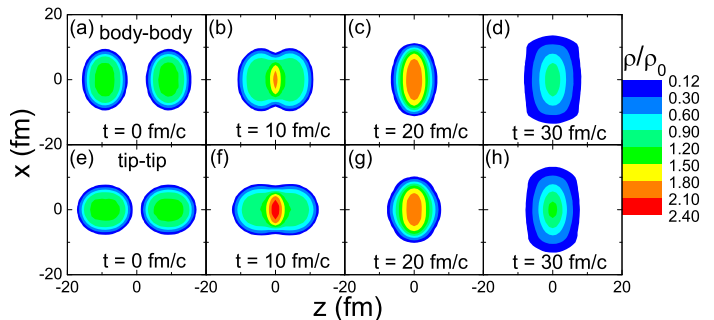


FIG. 2: (Color online) Time evolution of the density contours in x-z plane for central body-body (upper panels) and tip-tip (lower panels) U+U collisions.

The neutron-proton differential transverse flow, different elliptic flows of neutrons and protons, pre-equilibrium neutron/proton ratio, and π^-/π^+ ratio are among the experimental observables known to be sensitive to the $E_{sym}(\rho)$ [19, 43]. In the following subsections, we will examine separately the sensitivity of these observables to the variation of $E_{sym}(\rho)$ in both tip-tip and body-body collisions at beam energy of 0.52 GeV/nucleon. We will also compare effects of the symmetry energy with those due to the collision geometry. Pre-equilibrium nucleons are identified as those becoming 'free' (nucleons with local densities $\rho < \rho_0/8$) earlier than 40 fm/c when the participant is well equilibrated. We found that our conclusions are not sensitive to different criteria of identifying pre-equilibrium nucleons. Besides the extreme collision geometries of body-body and tip-tip collisions, as a reference we also study sphere-sphere collisions by setting $\delta_n = 0$ and $\delta_p = 0$ in Eqs. (4) and (5). Although it is still very challenging, in the present study we assume that desired reaction orientations can be achieved by either initially polarizing the colliding nuclei or finally selecting special events using orientation triggers proposed in the literature. To simulate typical cases of central and non-central collisions, we generated events with impact parameters $b = 0$ fm and $b = b_{\max}/2$ where b_{\max} is about 12.4, 13.6, and 16.0 fm for tip-tip, sphere-sphere, and body-body collisions, respectively. In each case about 200,000 events are generated for analysis.

A. Neutron-proton differential transverse flow

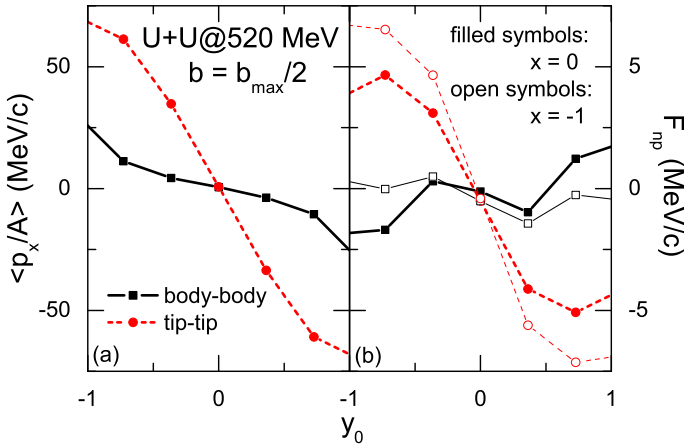


FIG. 3: (Color online) Transverse flow (a) and neutron-proton differential transverse flow (b) from non-central U+U collisions at beam energy 0.52 GeV/nucleon with different collision geometries and symmetry energies.

It is well known that the transverse flow is a useful probe of the nuclear EOS. Generally, since the isovector potential is relatively small compared to the isoscalar potential, the transverse flow is dominated by effects of the EOS of symmetric nuclear matter and nucleon-nucleon scatterings. The transverse flow in non-central U+U collisions as a function of reduced rapidity $y_0 = y/y_{\text{beam}}$, where y_{beam} is the beam rapidity in the center-of-mass frame, is shown in the panel (a) of Fig. 3. Similar to the finding in Ref. [11], the transverse flow is found to be much larger in tip-tip collisions than in body-body collisions due to the longer duration time of the high-density phase, which leads to a more persisting pressure, and stronger participant squeeze-out and spectator bounce-off effects [44] due to the collision geometry in the former case.

To probe the isovector potential and thus the symmetry energy, it is more useful to use the neutron-proton differential transverse flow which minimizes effects of the EOS of symmetric nuclear matter and nucleon-nucleon scatterings but adds up constructively effects due to the positive and negative symmetry potentials of neutrons and protons, respectively [45]. As shown in the panel (b) of Fig. 3, a stiffer symmetry energy ($x = -1$) leads to a larger neutron-proton differential flow, reflecting a larger difference of neutron and proton transverse flow. It is shown that the neutron-proton differential transverse flow is always larger in tip-tip collisions than in body-body collisions, and it is even larger from a soft symmetry energy in tip-tip collisions than that from a stiff symmetry energy in body-body collisions. Thus, effects of the collision geometry on neutron-proton differential transverse flow are much larger than those of the sym-

metry energy. The slope parameters $(dF_{np}/dy_0)_{y_0=0}$ in different cases are shown in Tab. I, where results from sphere-sphere collisions are also included for comparison. The slope parameter in tip-tip collisions is more sensitive to the symmetry energy than that in the other two cases, and this is understandable as the total transverse flow in tip-tip collisions is the largest and is most sensitive to the mean-field potential. The neutron-proton differential transverse flow in tip-tip collisions of deformed nuclei is thus a better probe to determine the symmetry energy at supra-saturation densities compared with collisions of spherical nuclei.

TABLE I: Slope parameters (in MeV/c) of neutron-proton differential transverse flow with different collision geometries and symmetry energies in non-central U+U collisions.

	$\frac{dF_{np}}{dy_0}(x=0)$	$\frac{dF_{np}}{dy_0}(x=-1)$
body-body (non-central)	-1.75 ± 0.46	-2.64 ± 0.46
tip-tip (non-central)	-9.92 ± 0.49	-14.10 ± 0.48
sphere-sphere (non-central)	-5.15 ± 0.48	-7.68 ± 0.48

B. Elliptic flow

The elliptic flow has been used to study properties of hot and dense matter formed in the early stage of heavy-ion collisions at both relativistic and intermediate energies, see, e.g., Refs. [46] and [47]. To probe the high-density symmetry energy, we examine the transverse momentum (p_T) dependence of elliptic flow (v_2) for mid-rapidity ($|y_0| < 0.5$) pre-equilibrium nucleons in central and non-central U+U collisions from different collision geometries in the panel (a) of Fig. 4. In non-central U+U collisions, v_2 is negative for both tip-tip and body-body collisions, as the emission of pre-equilibrium nucleons suffers the shadowing effects from the cold spectators and they are mostly squeezed out in the direction perpendicular to the reaction plane. Due to the geometry shape, body-body collisions give a larger magnitude of v_2 . The elliptic flow vanishes in central tip-tip collisions due to symmetry as one expects. However, it is still considerable in central body-body collisions. These are all consistent with previous results in Refs. [11–13].

The elliptic flows of pre-equilibrium neutrons and protons are affected differently by the symmetry potential too. The difference of neutron and proton elliptic flows, especially at higher p_T , is thus a useful probe of $E_{\text{sym}}(\rho)$ as well. As shown in Tab. II, in central body-body U+U collisions, the expansion of participants does not suffer from the shadowing effects, and a more repulsive mean-field potential leads to a larger v_2 . Due to the more repulsive mean-field potential of neutrons than protons considering the combined effects of symmetry potential, Coulomb interaction, and initial eccentricity, the elliptic flow of neutrons is slightly larger (more negative) than

protons for a soft symmetry energy ($x = 0$), while the difference is larger for a stiff symmetry energy ($x = -1$). In non-central collisions the situation is a little different. As the expansion of the participant nucleons is blocked by the spectator nucleons, a more repulsive potential leads to a faster expansion of the participant matter and more nucleons are squeezed out perpendicular to the reaction plane, resulting in a more negative elliptic flow as discussed in Refs. [47, 48]. It is seen in Tab. II that the elliptic flow of neutrons is somehow less negative than that of protons, taking into account the combined effects of the symmetry potential, Coulomb interaction, and initial eccentricity. Similar results were obtained in Ref. [43] from UrQMD calculations. With a stiff symmetry energy, which leads to a more repulsive neutron potential and a less repulsive proton potential at high densities, the difference of high- p_T neutron and proton elliptic flow is smaller. It is seen that this difference is more sensitive to the symmetry energy in body-body than tip-tip and sphere-sphere collisions. This is again understandable as the total elliptic flow is the largest in body-body collisions. Thus, the elliptic flow difference between neutrons and protons in body-body U+U collisions is a better probe of $E_{\text{sym}}(\rho)$ than collisions of spherical nuclei of the same mass.

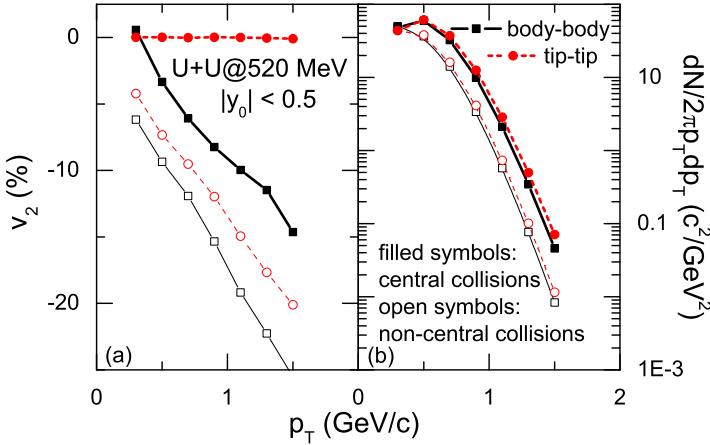


FIG. 4: (Color online) Transverse momentum dependence of the elliptic flow (a) and p_T spectra (b) of pre-equilibrium nucleons from central and non-central U+U collisions at beam energy 0.52 GeV/nucleon with different collision geometries. $x = 0$ is used in the calculation.

C. Pre-equilibrium neutron/proton ratio

The transverse momentum spectrum is known to be sensitive not only to the isoscalar potential and the nucleon-nucleon scattering cross section, but also the collision geometries in reactions involving deformed nuclei. As an example, the transverse momentum spectra of mid-

TABLE II: Mid-rapidity ($|y_0| < 0.5$) high- p_T ($p_T > 0.5$ GeV/c) neutron and proton elliptic flow difference (%) with different collision geometries and symmetry energies in central and non-central U+U collisions.

	$v_2(n) - v_2(p)$ ($x = 0$)	$v_2(n) - v_2(p)$ ($x = -1$)
body-body (central)	-0.02 ± 0.06	-0.26 ± 0.06
body-body (non-central)	1.46 ± 0.09	1.03 ± 0.09
tip-tip (non-central)	1.14 ± 0.08	0.93 ± 0.08
sphere-sphere (non-central)	1.21 ± 0.09	1.00 ± 0.08

rapidity ($|y_0| < 0.5$) pre-equilibrium nucleons from body-body and tip-tip collisions are shown in the panel (b) of Fig. 4. Similar to the finding in Ref. [11], the transverse momentum spectrum is stiffer in tip-tip than body-body collisions, as the high-density duration time is longer in tip-tip collisions and high- p_T nucleons are mainly emitted from the high-density regime.

It was first shown in Ref. [49] that the pre-equilibrium neutron/proton (n/p) ratio, which is insensitive to the isoscalar part of the nuclear EOS and the nucleon-nucleon scattering cross section, is a sensitive probe of the density dependence of nuclear symmetry energy. Due to the different p_T spectra of pre-equilibrium nucleons in body-body and tip-tip collisions, it is reasonable to expect that the high- p_T n/p ratio may depend on the collision geometry as well. To test this expectation, the neutron/proton ratio of pre-equilibrium nucleons from different cases are listed in Tab. III. The high- p_T n/p ratios are larger with a stiff symmetry energy ($x = -1$) due to the larger symmetry potential as expected, and it is larger in non-central collisions than in central collisions as a result of more neutron-rich participants in non-central collisions. In addition, it is more sensitive to the symmetry energy in central collisions than in non-central collisions. In spite of the small symmetry energy effect in the current collision energy, the n/p ratio is found to be slightly more sensitive to the symmetry energy in tip-tip collisions than in the other two cases. Moreover, the geometrical effect is rather small especially in central collisions compared with the symmetry energy effect.

TABLE III: Mid-rapidity ($|y_0| < 0.5$) high- p_T ($p_T > 0.5$ GeV/c) neutron/proton ratios with different collision geometries and symmetry energies in central and non-central U+U collisions.

	N_n/N_p ($x = 0$)	N_n/N_p ($x = -1$)
body-body (central)	1.248 ± 0.001	1.283 ± 0.001
tip-tip (central)	1.241 ± 0.001	1.286 ± 0.001
sphere-sphere (central)	1.246 ± 0.001	1.284 ± 0.001
body-body (non-central)	1.292 ± 0.002	1.300 ± 0.002
tip-tip (non-central)	1.281 ± 0.001	1.295 ± 0.001
sphere-sphere (non-central)	1.290 ± 0.002	1.300 ± 0.002

D. π^-/π^+ ratio

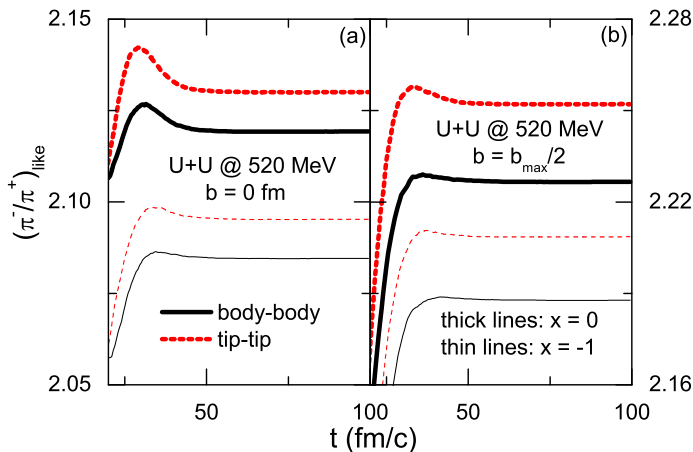


FIG. 5: (Color online) Time evolution of the $(\pi^-/\pi^+)_{\text{like}}$ ratio in central (a) and non-central (b) U+U collisions with different collision geometries and symmetry energies, in which the contributions from Δ resonances are taken into consideration.

The π^-/π^+ ratio is a sensitive tracer of the isospin asymmetry of the high-density participants [50] which is essentially determined by the $E_{\text{sym}}(\rho)$ through the isospin fractionation process, as neutron-neutron (proton-proton) collisions produce mostly Δ^- (Δ^{++}) resonances which decay into π^- (π^+). A more systematic analysis has demonstrated that the π^-/π^+ ratio is more sensitive to the symmetry energy at supra-saturation densities but insensitive to that at subsaturation densities [51]. Figure 5 displays the time evolution of $(\pi^-/\pi^+)_{\text{like}}$ ratio, in which the contributions from Δ resonances are taken into account, from different symmetry energies and collision geometries in both central and non-central U+U collisions. A soft symmetry energy leads to a larger $(\pi^-/\pi^+)_{\text{like}}$ ratio as expected, although the symmetry energy effects with $x = 0$ and $x = -1$ are not large for the collision energy studied here. However, it is interesting to note that the resulting $(\pi^-/\pi^+)_{\text{like}}$ ratio is higher in tip-tip collisions. Effects of the collision geometry on the final π^-/π^+ ratio are small but still around 30% of those due to the symmetry energy in central collisions, and they are even larger in non-central collisions. This is mainly because pions are strongly affected by the final state reabsorption and re-emission. The π^-/π^+ ratio is thus affected significantly differently by the different path-lengths in collisions of various geometries. Nevertheless, we found that the sensitivities of the π^-/π^+ ratio to the symmetry energy are similar for different orientations. To be more quantitative, values of the final π^-/π^+ ratio in different cases are listed in Tab. IV.

TABLE IV: π^-/π^+ ratios with different collision geometries and symmetry energies in central and non-central U+U collisions.

	$\pi^-/\pi^+ (x = 0)$	$\pi^-/\pi^+ (x = -1)$
body-body (central)	2.119 ± 0.002	2.085 ± 0.002
tip-tip (central)	2.130 ± 0.002	2.095 ± 0.002
sphere-sphere (central)	2.123 ± 0.002	2.091 ± 0.002
body-body (non-central)	2.227 ± 0.003	2.188 ± 0.003
tip-tip (non-central)	2.252 ± 0.003	2.209 ± 0.003
sphere-sphere (non-central)	2.245 ± 0.003	2.197 ± 0.003

IV. SUMMARY

We studied the effects of the collision geometry on observables that are known to be sensitive to the nuclear symmetry energy, such as the neutron-proton differential transverse flow, the difference of neutron and proton elliptic flow, the pre-equilibrium neutron/proton ratio and the π^-/π^+ ratio in U+U collisions. We found that the neutron-proton differential transverse flow is always larger in tip-tip than body-body collisions, and it is more sensitive to the symmetry energy in the former case. On the other hand, the difference of neutron and proton elliptic flow is more sensitive to the symmetry energy in body-body than tip-tip collisions. In addition, the n/p ratio of pre-equilibrium nucleons is slightly more sensitive to the symmetry energy in tip-tip collisions. Moreover, the collision geometry is found to affect significantly the π^-/π^+ ratio.

As the collision geometry effects are comparable to or sometimes even larger than the symmetry energy effects, one should be careful when studying isospin-sensitive observables in collisions involving deformed nuclei. Large errors may be induced by assuming that the colliding nuclei are spherical priorly. In addition, using deformed nuclei, the neutron-proton differential transverse flow in tip-tip collisions and the difference of neutron and proton elliptic flow in body-body collisions are better probes for symmetry energy at supra-saturation densities compared with collisions of spherical nuclei.

Acknowledgements

We thank Dr. Derek Harter and Dr. Sam Saffer for making available to us facilities at the high-performance Computational Science Research Cluster at Texas A&M University-Commerce. Zachary Martinot would like to thank the NSF funded REU (Research Experience for Undergraduates) program at Texas A&M University-Commerce for the opportunity of participating in the research reported in this paper. We would also like to thank Dr. W. G. Newton and Dr. F. J. Fattoyev for helpful discussions. This work was supported in part by the US National Science Foundation grants PHY-0757839, PHY-1068022 and REU grant no. 1062613 as well as the National Aeronautics and Space Administration under grant NNX11AC41G issued through the Science Mission

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